BBC RD 1973/7

1968
THE QUEEN'S AWARD TO INDUSTRY

RESEARCH DEPARTMENT

REPORT

DIGITAL VIDEO:
differential coding of PAL signals based on differences between samples one subcarrier period apart

V.G. Devereux, M.A.

Research Department, Engineering Division
THE BRITISH BROADCASTING CORPORATION June 1973 (EL-78)

BBC RD 1973/7
UDC 621.376.56
621.397.2

DIGITAL VIDEO: DIFFERENTIAL CODING OF PAL SIGNALS BASED ON DIFFERENCES BETWEEN SAMPLES ONE SUBCARRIER PERIOD APART

V.G. Devereux, M.A.

Summary

Methods for reducing the bit-rate required for digital coding of System I (PAL 625-line) video signals by means of differential pulse code modulation are discussed. The subjective effect of various d.p.c.m. and hybrid d.p.c.m./p.c.m. coding systems have been investigated with a view to finding a system giving broadcast quality pictures. All the systems examined would require the transmission of either five or six bits per sample at a sampling frequency which is thrice the PAL colour subcarrier frequency, i.e. 13·3 MHz. The d.p.c.m. codes used in most experiments indicate the change in level between every third sample of the video signal, but the possibility of conditional operation using adjacent samples was also examined.

The results of subjective tests indicated that for a single coding and decoding operation, broadcast quality pictures can be obtained using five bits per sample. In practice, however, up to two extra bits would probably be required per sample to allow for several coders and decoders in tandem and for error protection.

Issued under the authority of

P. Rainger

Head of Research Department

Research Department, Engineering Division,
BRITISH BROADCASTING CORPORATION

(EL-78)

DIGITAL VIDEO: DIFFERENTIAL CODING OF PAL SIGNALS BASED ON DIFFERENCES BETWEEN SAMPLES ONE SUBCARRIER PERIOD APART

(EL-78)

BBC RD 1973/7
UDC 621.376.56
621.397.2

DIGITAL VIDEO: DIFFERENTIAL CODING OF PAL SIGNALS BASED ON DIFFERENCES BETWEEN SAMPLES ONE SUBCARRIER PERIOD APART

V.G. Devereux, M.A.

1. Introduction

The bit rates required for the transmission of broadcast quality video signals in digital form are necessarily high, and in order to reduce transmission costs, there is a demand for improved methods of coding to reduce the rates below the figure of 100 – 120 Mb/s required for linear pulse code modulation (p.c.m.).[1,2] Work has therefore been carried out to examine the possibility of reducing the bit-rate required for digital coding of System I (PAL, 625-line) video signals by means of certain forms of differential pulse code modulation (d.p.c.m.) that could be easily implemented in a transmission system. These bit saving techniques may also contribute in overcoming problems involved in the recording of digital video signals.

Various d.p.c.m. and hybrid d.p.c.m./p.c.m. systems have been constructed. In all the systems investigated, the PAL video signal was sampled at three times the colour subcarrier frequency and the d.p.c.m. code indicated the change in level since either the previous sample or the third previous sample. As explained later in this report, the encoding of difference between adjacent samples is more suitable for monochrome pictures, while encoding differences between every third sample is more suitable for colour pictures.

The report first discusses general principles of d.p.c.m. and then describes the design of experimental equipment, followed by the results of subjective tests.

2. General principles of differential pulse code modulation

In any video signal, there is a relatively high correlation between the information contained in samples corresponding to closely adjacent parts of the picture, whether taken from the same line, adjacent lines in the same field or from successive fields.[3,4,5] D.P.C.M. is a technique which exploits implied redundances by the use of a transmission code which represents the difference between each sample of a video signal and a predicted value of that sample based on previously transmitted sample values. A simple but effective prediction system for monochrome pictures uses the value of the previously transmitted sample as the prediction for the following sample. By arranging that the d.p.c.m. coder and decoder both make the same prediction of each sample, signal samples can be recovered in the decoder by adding the transmitted differences to the predicted sample values.

In order to obtain any reduction in the bit rate by means of d.p.c.m., the coder must include a non-linear quantiser which quantises small differences more accurately than large differences. Quantising errors are therefore minimised by making the prediction system as accurate as possible and by optimising the quantising law to suit the probability statistics of the difference signal.

O'Neal[6] found that, for monochrome pictures, a d.p.c.m. system in which the predicted sample value was equal to the transmitted value of the previous sample gave r.m.s. quantising errors about 15 dB lower than a p.c.m. system using the same number of bits per sample. This improvement varied by about 2 to 3 dB depending on the picture material used in his tests. When the predicted sample was given by the mean value of the previous sample on the same line and a vertically adjacent sample on the previous line in the same field period, the r.m.s. quantising error was reduced by a further 2 or 3 dB. The inclusion of other sample values from the same field gave only a marginal improvement in the prediction process; the use of samples from spatially adjacent lines in previous field periods was not considered.

A block diagram of a d.p.c.m. system as outlined above is shown in Fig. 1 where A represents the value of a sample of the video signal at the input of the coder and B represent the predicted value of this sample. E represents the magnitude of the quantising error introduced by the non-linear quantiser. The channel encoder converts the output levels of the non-linear quantiser into a suitable transmission code and the channel decoder performs an exactly inverse process to re-establish the correct value of $A-B+E$ in the decoder. Both the coder and decoder integrate the quantised difference signals in the feedback loop containing the adder and predictor. Since these two integrators are identical, both the coder and decoder derive identical values of the predicted signal B and of the decoder output $A+E$ assuming no transmission errors have occurred.

For a previous-sample prediction system, the predictors shown in Fig. 1 would consist of a delay of one sample period followed by an amplifier of approximately unity gain as shown in Fig. 2. O'Neal has shown that the gain A_1 of the amplifier should ideally be slightly less than unity. A predictor including information from the previous line as well as the previous sample is shown in Fig. 3 where A_2 and A_3 should both be equal to about ½.

The most noticeable forms of picture impairment introduced by d.p.c.m. systems using previous sample pre-

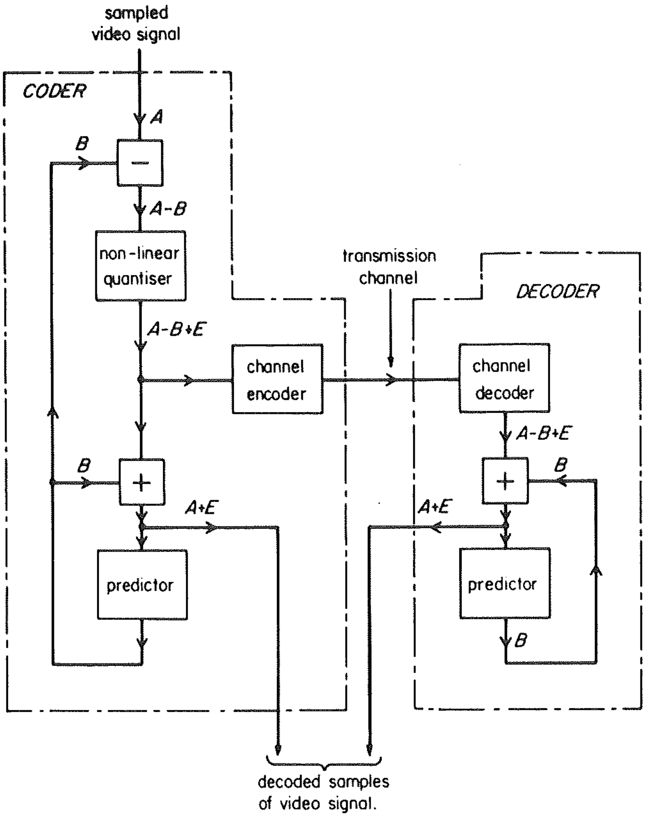


Fig. 1 - Block diagram of d.p.c.m. coder and decoder

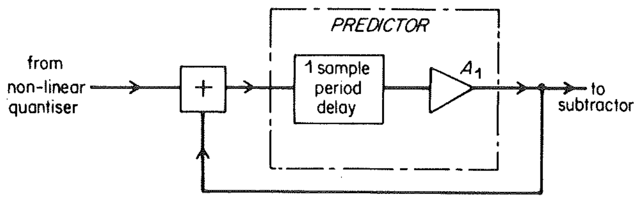


Fig. 2 - Previous sample predictor

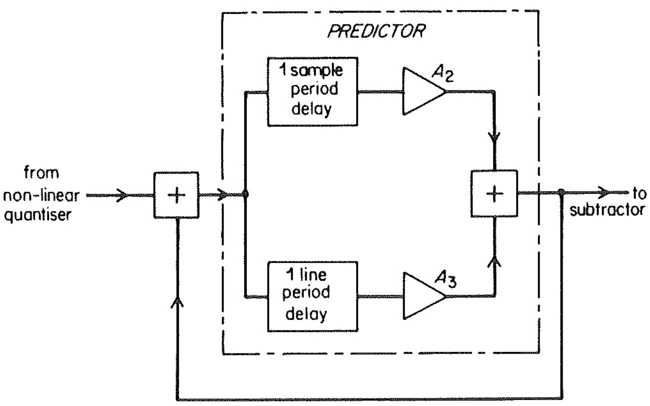


Fig. 3 - Previous line and previous sample predictor

diction occur near vertical edges in the picture detail and are known as 'slope overload' and 'edge busyness'. 'Slope overload' appears as a streaking effect and occurs when the magnitude of the difference signal is well in excess of the largest difference which can be conveyed by the non-linear quantising law. 'Slope overload' would not normally be allowed to occur in a d.p.c.m. system for broadcast quality video signals. 'Edge busyness' appears as noise on vertical edges and results from the coarse quantisation of large differences within the outer limits of the quantising law.

3. Differential coding of colour television signals

Using a previous-sample prediction system (i.e. a system in which the differences between successive samples are coded) any reduction in bit rate is obtained at the expense of large quantising errors in high-amplitude, high-frequency components of the video signal. This characteristic is compatible with the requirements of efficient coding of most monochrome pictures since, in general, they contain far more low frequency than high frequency information and, also, quantising errors in high frequency detail tend to be less visible than quantising errors in plain areas of a picture. With composite colour signals however, the colour subcarrier components can cause a high proportion of large differences which should be encoded with about the same accuracy as used for small differences. In practice, it has been found that, for a given degree of impairment, the bit-rate required for 625 PAL colour video signals using a d.p.c.m. system with previous sample prediction is about the same as that required using p.c.m.

The problem of accurate d.p.c.m. coding of the colour subcarrier components can be largely overcome by a development of a technique used in error concealment in linear p.c.m.[7] The resulting d.p.c.m. system[8] uses a sampling frequency equal to 'n' times the colour subcarrier frequency and the prediction corresponds to a previous sample separated by n sample periods where n is an integer. For composite colour signals, the most practical choice for n is a value of 3, giving a sampling frequency for the PAL 625 line system of 13·3 MHz. Since the time interval between every third sample is then equal to one cycle of the colour subcarrier, the differences caused by the presence of colour subcarrier are small (see Fig. 4) and are therefore accurately encoded. Similarly, if samples from previous lines or fields are used in the prediction process for signals including colour subcarrier, they should have occurred an integral number of cycles of subcarrier previous to the sample being encoded. For PAL signals, complications arise due to the switching of the phase of the (R−Y) colour difference signal on alternate lines, but, in this report, we are only concerned with the use of the third previous in the same line to achieve accurate encoding of colour subcarrier.

The main disadvantage of third-previous-sample prediction compared with previous-sample prediction is that it is less accurate during rapid transitions in the luminance component of the video signal (see Fig. 4). In an attempt at overcoming this problem, an adaptive prediction system was investigated which normally used third-previous-sample prediction but automatically switched to previous-sample prediction when large difference signals were obtained. This adaptive prediction is discussed in more detail in Section 5.4.

In an alternative method of applying d.p.c.m. to the coding of colour signals, separate d.p.c.m. encoders are used

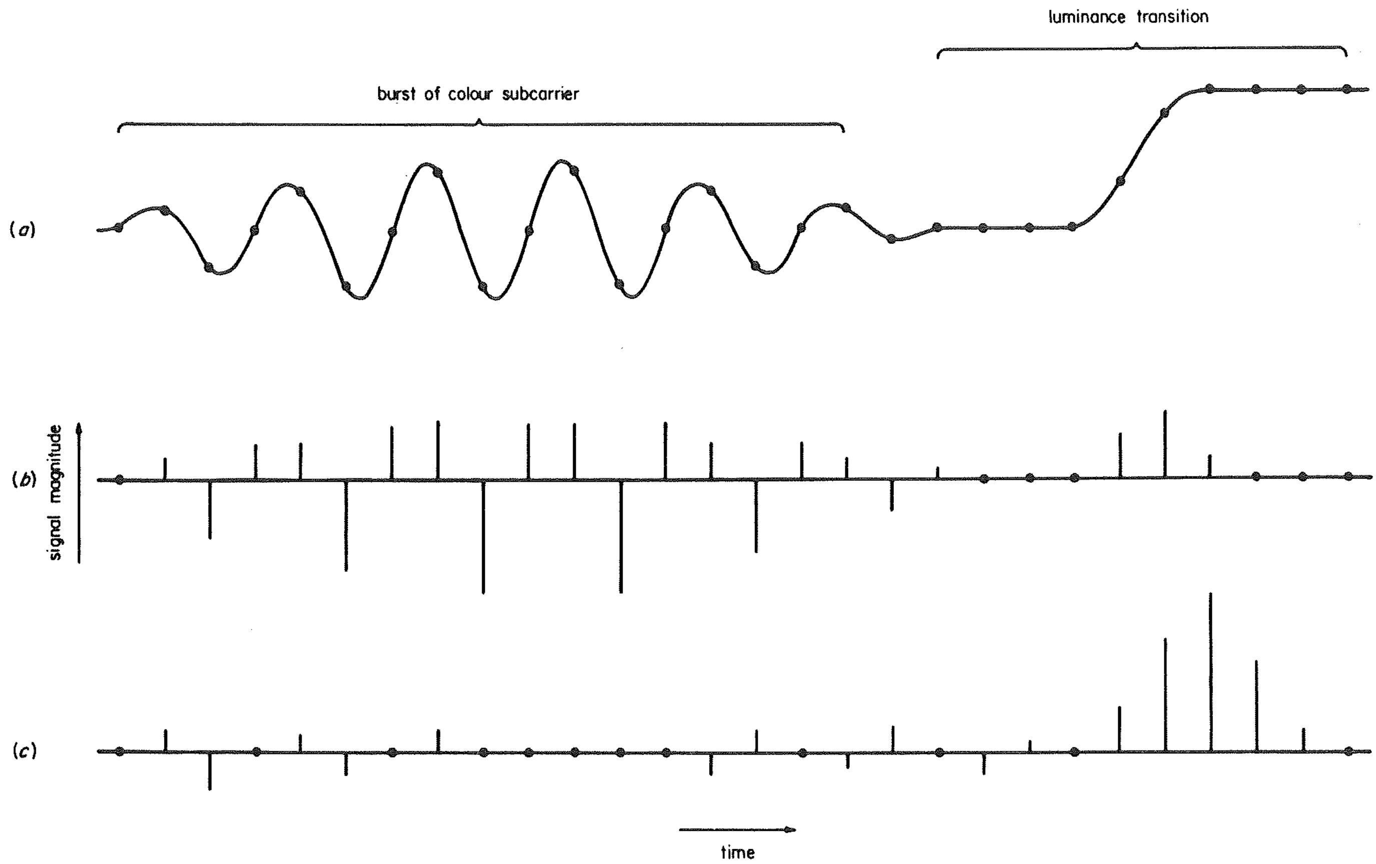


Fig. 4 - Magnitude of differences between adjacent samples and between every third sample for a sampling frequency equal to three times colour subcarrier frequency

(*a*) Analogue video signal • indicates sampling points (*b*) Differences between adjacent samples (*c*) Differences between every third sample

for the luminance and two colour difference signals.[9,10] This method has the advantage that as no subcarrier is present, previous sample rather than third previous sample prediction can be used for both the luminance and colour signals. It has the disadvantage, however, that if a digital link is connected between analogue links carrying PAL video signals, then PAL decoding and re-encoding operations would be required before and after the digital link and these operations would cause a noticeable degradation of picture quality.[11] No further consideration is therefore given to this form of coding in this report.

4. Effect of transmission errors in d.p.c.m. and hybrid d.p.c.m./p.c.m. systems

The main disadvantage of d.p.c.m. systems is that any transmission error causes incorrect values of all the following decoded samples until the integrator in the decoder is reset to its correct value.[12] Resetting of the decoder is accomplished by transmitting a p.c.m. value of A rather than the d.p.c.m. value $A-B+E$, and, at the same time, the predicted signal B should be set to zero. For video signals, the line blanking intervals provide convenient periods in which to reset the decoder; the effect of transmission errors is then terminated at the end of each line period.

In order to reduce the number of video samples affected by a transmission error, hybrid p.c.m./d.p.c.m. systems have been investigated in which p.c.m. sample values are transmitted during the parts of the video signal carrying picture information.[13] (See Section 5.3.)

The remarks given above are based only on theoretical considerations and the practical results obtained by other workers.[12] The subjective effect of transmission errors could not be examined using the experimental equipment described in this report because, as explained in Section 5.1, this equipment did not include a transmission channel or decoder.

5. Design of experimental equipment

5.1. General details

Equipment was constructed to examine the picture impairment introduced by several different d.p.c.m. and hybrid p.c.m./d.p.c.m. coding systems. A block diagram of a coder and decoder which is applicable to all the systems investigated is shown in Fig. 5.

For accuracy and ease of instrumentation, all processing was performed in the digital domain. The input to the equipment was the output of an 8-bit video analogue-to-digital converter (a.d.c.)[14] sampling at 3 times colour subcarrier frequency; the output of the equipment was fed to an 8-bit digital-to-analogue converter (d.a.c.). With

switches S1, S2 and S3 in the positions shown in Fig. 5, the system is similar to that shown in Fig. 1 and a d.p.c.m. code is transmitted; reversing the positions of these switches gives a p.c.m. code.

The predictor used in this equipment consisted of a delay of T_S or $3T_S$ with unity gain, where T_S is equal to the time between sampling instants. This delay could be switched either manually or electronically as discussed in Section 5.4.

In describing the operation of the coder and decoder it is convenient to relate all signal values to the values A and B of the signals at the inputs to the subtractor.

The values of A produced by the p.c.m. range limiter are equal to the input video sample values which can vary between 0 and 255 (using decimal equivalents of binary numbers) except that input values 0 to 6 are changed to 7 and input values 248 to 255 are changed to 247. This limitation of the range of values of A prevents arithmetic processing errors as discussed in the Appendix, Section 9.1.

The value of B, used as a prediction for A, is equal to the decoded value of the sample occurring either three sample periods or one sample period before the sample A depending on whether the delay is switched to $3T_S$ or T_S.

E_1 and E_2 represent the quantising errors introduced in the d.p.c.m. non-linear quantiser and in the p.c.m. processor respectively. E_1 and E_2 are also equal to the errors introduced into each sample value in passing through a complete coder/decoder combination.

It will be noticed that both the coder and decoder contain identical arrangements of adder, predictor and switch. Also, the signals entering the unswitched inputs of the adders in the coder and decoder are identical since the 8 to N bit and N to 8 bit converters perform inverse operations. As a result, the coder generates a signal $A + E_1$ or $A + E_2$ which is identical to the output signal from the decoder. Therefore, in order to minimise the instrumentation required to examine the subjective effect of quantising errors, only the coder was constructed.

All video signals within the coder which have been indicated in terms of A or B are represented in practice by 8-bit binary numbers in parallel form. The 9-bit numbers obtained from the adder and subtractor are reduced to 8-bits by ignoring their most significant bit; as a result, the rules of modulo 256 arithmetic must be applied as discussed in Section 9.1. Signals with a reduced number of bits per

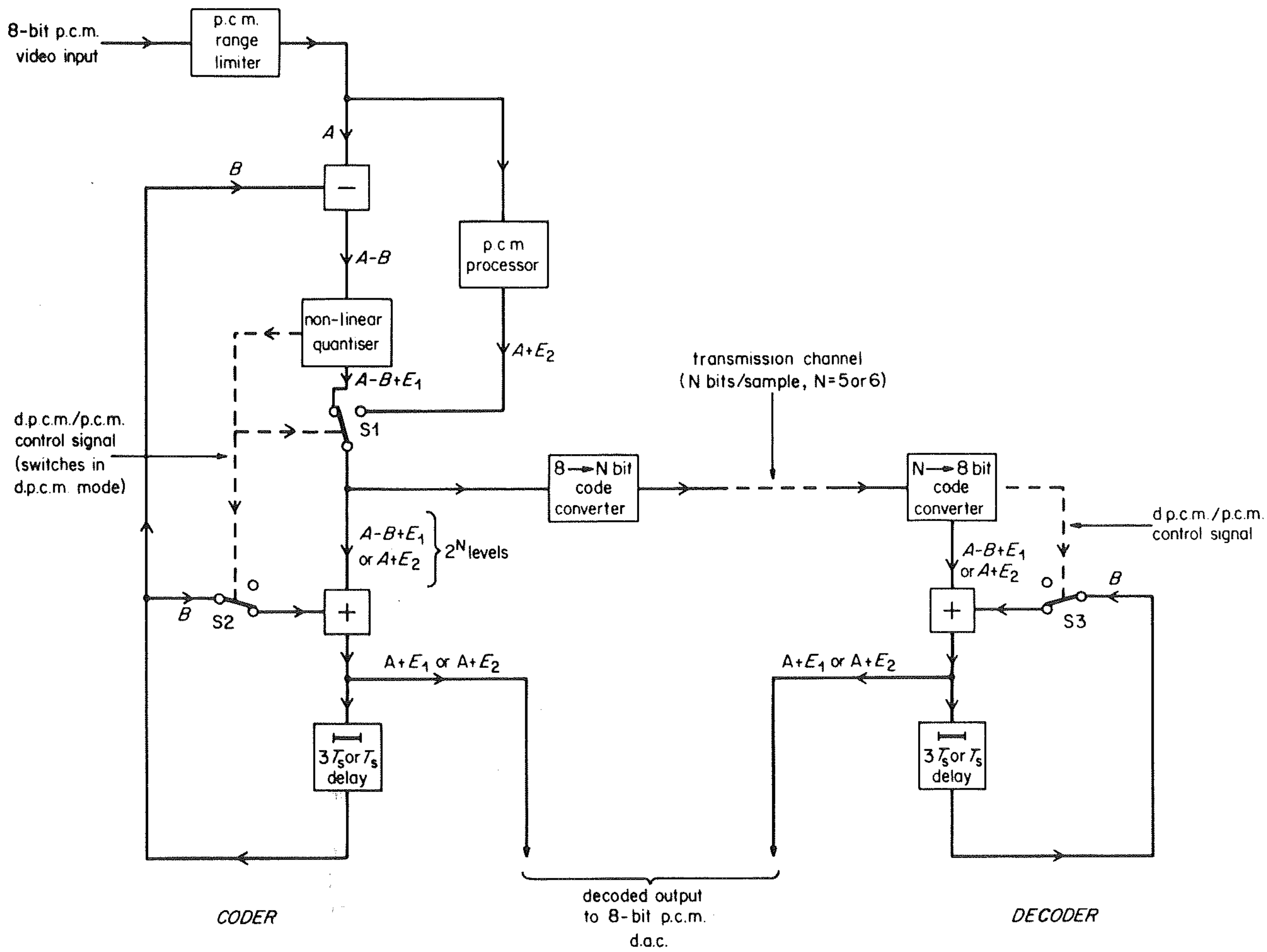


Fig. 5 - Block diagram of p.c.m./d.p.c.m. coder and decoder

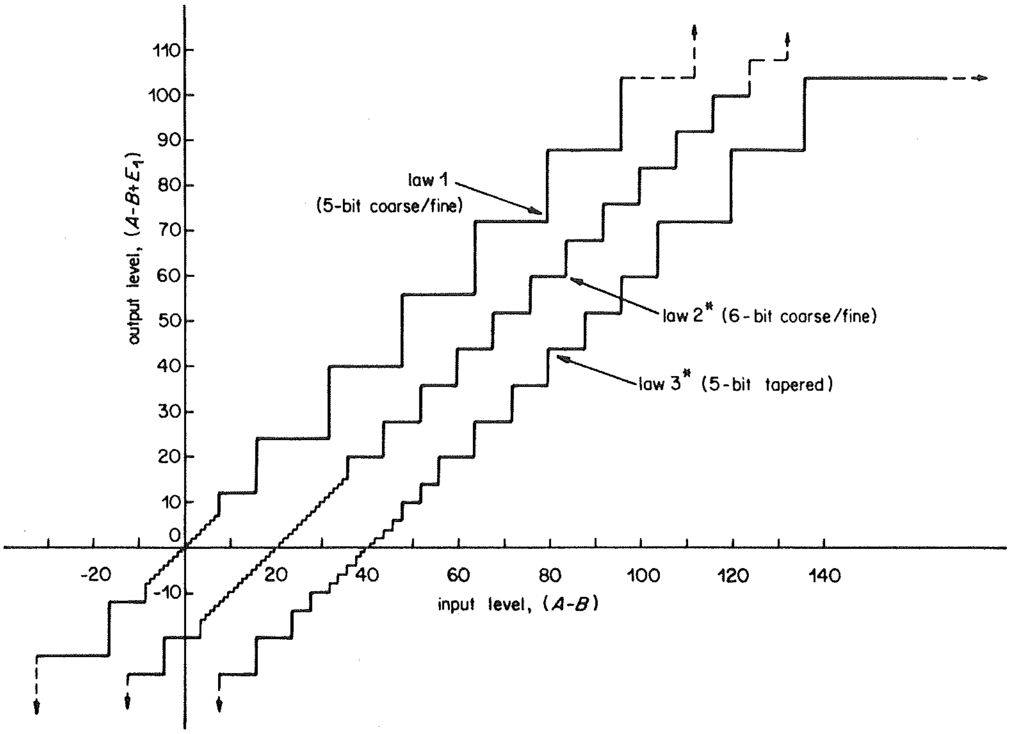


Fig. 6 - D.P.C.M. non-linear quantising laws

*For clarity, Laws 2 and 3 have been shifted horizontally by 20 and 40 levels respectively. In practice, all Laws pass through the origin

sample N, less than 8, only occur in the transmission channel. In order to make a transmission code with N bits possible, the signal processing must reduce the number of possible values of the 8-bit input signal of the 8 to N bit code converter to 2^N.

The following Sections describe the operation of the coder in more detail.

5.2. Quantising laws for d.p.c.m.

As mentioned previously, switches S1 and S2 should be in the positions shown in Fig. 5 for the coder to operate in the d.p.c.m. mode. In this mode of operation, three different non-linear quantising laws were examined. The characteristics of these are shown in Fig. 6 and the main details are summarised in Table 1; all signal values have been given as the decimal equivalents of the binary numbers occurring in the coder. In Table 1, the 'size of difference' has been divided into 'large' and 'small' ranges for convenience in later discussions.

With the coarse/fine laws (Laws 1 and 2) in use, 'small' differences are transmitted with the same accuracy as in an 8-bit p.c.m. system while for 'large' differences the mean quantising errors are the same as would be provided by 4 and 5-bit p.c.m. systems respectively. For both these laws, the input/output characteristics continue in the manner indicated for large differences up to the maximum possible values of the difference signal i.e. up to ±256; the resulting number of output levels are 48 and 92 respectively. It will be noticed that the number of output levels required for these laws exceeds the number of digit combinations provided by 5 and 6-bit transmission codes. This problem

TABLE 1

Non-linear quantising laws for d.p.c.m. systems

Bits per sample	Description of Law	Size of Difference $\lvert A-B \rvert$	No. of output levels	Error $\lvert E_1 \rvert$
5	Coarse/fine Law 1	$\leqslant$ 8 (Small) $>$ 8 (Large)	16 32	0 $\leqslant$ 8
6	Coarse/fine Law 2	$\leqslant$ 16 (Small) $>$ 16 (Large)	32 60	0 $\leqslant$ 4
5	Tapered Law 3	$\leqslant$ 24 (Small) 25 to 104 (Large) $>$ 104 (Large)	16 16 None	$\leqslant$ 4 $\leqslant$ 8 $\leqslant$ 152

may be overcome, however, by arranging that the same digit combination is transmitted for both a 'large' positive difference d and a 'large' negative difference equal to $(d - 256)$. This process halves the number of digit combinations required for 'large' differences and reduces the effective number of output levels which need to be transmitted to 32 and 62 thus making it possible to use 5 and 6 bit codes respectively. In the decoder, the correct choice between the two possible values for large differences can be resolved by making use of the fact that the output signal $A + E_1$ must have a value lying within the range 0 to 255. Further practical details are given in the Appendix, Section 9.2.

Considering the 5 bit tapered law (Law 3) it will be seen from Fig. 6 that the coding accuracy progressively decreases as the magnitude of the difference signal increases and the maximum difference value which can be transmitted is ±104. This limitation at ±104 causes very little slope overload distortion since a full black to white transition in the video signal results in a difference signal of only about 120, assuming that the peak-to-peak amplitude of the PAL video signal applied to the initial p.c.m. coder is adjusted to be about 1·8 dB less than the conversion range, as suggested in a previous report.[1]

Law 3 has 32 output levels which can obviously be represented by a 5-bit transmission code. If desired, further output levels could be transmitted by using the same code for two different output levels as discussed in relation to Laws 1 and 2. For example, the code for 104 could also be used to indicate a difference of −152. Including ±152 as output levels would have the disadvantage, however, that it would increase the maximum value of the error E_1 in a manner that could cause arithmetic decoding errors unless the p.c.m. range limiter further restricted the values of A to the range from 24 to 231. The number of available p.c.m. levels would thus be reduced from 240 to 208 which would effectively increase quantising errors by 1·3 dB. It is considered that this effect is less desirable than the occurrence of very occasional slope overload obtained with no levels at ±152.

More detailed information concerning Law 3 is given in the Appendix, Section 9.3.

5.3. Quantising laws for p.c.m./d.p.c.m.

Three hybrid p.c.m./d.p.c.m. systems corresponding to the three d.p.c.m. quantising laws shown in Table 1 were examined. In all these hybrid systems, d.p.c.m. is used for coding 'small' differences and p.c.m. is used when 'large' differences occur. In the p.c.m. mode, either the first 4 or the first 5 most significant bits of the absolute value of A would be transmitted depending on whether the transmission code has 5 or 6 bits per sample. The characteristics of the hybrid p.c.m./d.p.c.m. quantising laws are summarised in Table 2.

In practice, the p.c.m. mode is obtained by the automatic operation of switches S1 and S2 to the opposite positions from those shown in Fig. 5. Coarsely quantised p.c.m. sample values $A + E_2$ then appear at both the input and output of the adder in the coder. In a system including a decoder, S3 would also be operated. For the systems giving 5-bit transmission codes, the 8 bits of $A + E_2$ are given by the four most significant bits of A followed by 1, 0, 0, 0 as the four least significant bits. For the 6-bit system, $A + E_2$ is given by the five most significant bits of A followed by 1, 0, 0 as the three least significant bits.

As mentioned in Section 4, one of the main advantages of hybrid d.p.c.m./p.c.m. systems is that the presence of p.c.m. sample values terminates the effect of transmission errors more rapidly than is possible in a d.p.c.m. system. In order to improve this ruggedness against transmission errors, additional p.c.m. values could be transmitted in the following manner. With a 5-bit law in use, it can be arranged that the p.c.m. mode of operation is used, regardless of the size of the difference signal, whenever the 4 least significant bits of A happen to be equal to 1000. Since both the coder and decoder automatically set the 4 least significant bits of $A + E_2$ to 1000 in the p.c.m. mode, these sample values are transmitted with 8-bit accuracy. This use of the p.c.m. mode would apply to 16 different values of A. Similarly, with the 6-bit law in use, p.c.m. values

TABLE 2

Non-linear quantising laws for hybrid p.c.m./d.p.c.m. systems

Bits per sample	Description	Details	Error $\lvert E_1\rvert$ or $\lvert E_2\rvert$
5	Coarse/fine	D.P.C.M., Law 1, for $\lvert A-B\rvert \leqslant 8$	0
		4 bit p.c.m. for $\lvert A-B\rvert > 8$	$\leqslant 8$
6	Coarse/fine	D.P.C.M., Law 2, for $\lvert A-B\rvert \leqslant 16$	0
		5 bit p.c.m. for $\lvert A-B\rvert > 16$	$\leqslant 4$
5	Tapered	D.P.C.M., Law 3, for $\lvert A-B\rvert \leqslant 24$	$\leqslant 4$
		4 bit p.c.m. for $\lvert A-B\rvert > 24$	$\leqslant 8$

would be transmitted whenever A happened to be equal to one of the 32 values whose 8-bit code had 100 as the three least significant bits.

5.4. Method of prediction

The prediction given by the T_S or $3T_S$ delay could be set manually to operate in three different modes. It could be set to provide a delay of T_S or $3T_S$ for all samples or it could be set to an adaptive mode in which it automatically switched between delays of T_S and $3T_S$ according to signal conditions. In this adaptive mode, the T_S delay was used only for the three samples following a sample causing a large difference with the $3T_S$ delay in use. (Large differences are as defined in Table 1.) The $3T_S$ delay was then re-inserted until the next large difference was obtained when the process was repeated. By setting both the coder and decoder to follow the same rules, it is unnecessary to transmit any information to indicate which of the delays should be in use.

This adaptive mode of prediction was designed as an attempt to achieve more accurate prediction during rapid luminance transitions than that obtained using third-previous-sample prediction alone.

6. Subjective tests

6.1. Initial investigations

The experimental equipment was capable of providing 18 different methods of processing video signals; there were six different methods of quantising (three for d.p.c.m. and three for hybrid p.c.m./d.p.c.m.) and three different prediction systems. In order to reduce the number of formal subjective tests, preliminary tests were carried out to select the processing methods of greatest interest.

Previous sample prediction was obviously not as good for coding colour signals as the third previous sample or the adaptive prediction systems due to the increased quantising errors in plain coloured areas of a picture. For monochrome signals, however, previous sample prediction was noticeably better than the other two prediction systems due to the reduction in the visibility of edge busyness effects. Since the purpose of the work was primarily to determine the optimum method of coding PAL colour signals, previous-sample prediction alone was not included in the formal subjective tests.

The number of tests was further reduced by omitting tests on d.p.c.m. coarse/fine quantising laws (Laws 1 and 2) since it was found that they gave almost identical picture quality to the corresponding hybrid p.c.m./d.p.c.m. coarse/fine laws. This similarity was to be expected since the use of p.c.m. instead of d.p.c.m. for large differences does not affect the r.m.s. value of the quantising errors for these two laws. The hybrid systems were examined in preference to d.p.c.m. systems as they provide additional ruggedness against the effects of transmission errors. With the tapered quantising law, however, the quantising errors obtained for large differences are by no means the same for the hybrid p.c.m./d.p.c.m. and d.p.c.m. laws and therefore both types of coding were examined.

The initial tests also showed that the main improvement given by the 6-bit coarse/fine quantising law over the 5-bit coarse/fine law was a marked reduction in edge busyness effects resulting from the use of 5-bit coding accuracy instead of 4-bit accuracy for large difference signals. This was one of the main factors taken into account in the 5-bit tapered quantising law which was designed after the effects of using the coarse/fine laws had been observed. The 5-bit tapered law gives an accuracy of 5 bits per sample or better for difference values between −56 and +56 whereas the accuracy of the 5-bit coarse/fine law drops to 4-bit accuracy for differences greater than ±16.

In the formal tests described in Section 6.2, only a colour monitor was used for examining picture quality as preliminary tests showed that any picture impairments were at least as noticeable on a colour monitor as on a monochrome monitor fed with same video signal.

6.2. Equipment used in subjective tests

In the 8-bit a.d.c.[14] prior to the d.p.c.m. coder, the video signal was clamped with the tips of synchronising pulses at the bottom of the conversion range and its amplitude adjusted so that the highest level reached by the sub-carrier in a 100% saturated colour bar signal was about 1 dB below the top of the conversion range (see Fig. 7). This margin of 1 dB ensured that the peak-to-peak range of the video signal was within the range which could be handled by the range limiter. In practice, clipping of the bottom of synchronising pulses by the range limiter was allowed to occur as it did not affect picture quality and it was therefore not considered worthwhile to alter the clamping potential in the a.d.c.

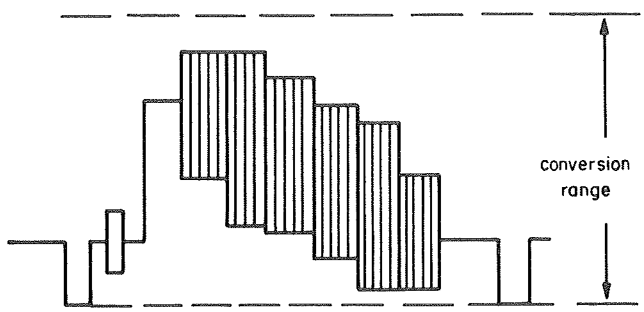


Fig. 7 - Setting of video signal levels in relation to the conversion range of the 8-bit analogue-to-digital converter shown for 100% colour-bars

The output signals $A + E_1$ or $A + E_2$ obtained from the d.p.c.m. coder were passed through an 8-bit d.a.c.[14] which included a 5·5 MHz low-pass filter and the resulting video signals were displayed on a high quality colour monitor with a screen diagonal size of 560 mm (22 in.). The peak brightness on the monitor screen was adjusted to be 80 cd/m^2; with zero beam current, the brightness of the screen resulting from ambient illumination was about 0·8 cd/m^2

All the pictures examined in the tests were obtained from a high quality 35 mm colour slide scanner. Five slides were used, these being selected to provide many well defined chrominance and luminance edges. Monochrome versions of these slides are shown in Fig. 8. In the tests, all slides were coloured except Slide 4.

6.3. Test procedure and results

Each test picture was shown twice to a group of five observers seated between five and seven times picture height from the picture monitor. The observers were all engineers experienced in assessing picture quality. Before the tests commenced, the types of impairment to be expected were pointed out to the observers. In addition, the unprocessed pictures were shown between each test picture.

Picture quality was graded using the 6-point impairment scale given below.

Grade	Degree of impairment
1	Imperceptible
2	Just perceptible
3	Definitely perceptible but not disturbing
4	Somewhat objectionable
5	Definitely objectionable
6	Unusable

Details of the results of the subjective tests for all the different systems which were examined are shown in Table 3. The figures in brackets under 'mean grade' give the standard deviation of the impairment grade resulting from changes in the picture material.

6.4. Discussion of results

The results of the tests showed that the five-bit coarse/fine systems were not of broadcast quality. The five-bit tapered p.c.m./d.p.c.m. law provided a noticeable improvement in quality but the best results for five bits per sample were obtained with the tapered, all d.p.c.m., law. The picture quality obtained with the six-bit coarse/fine law was nearly indistinguishable from the original, imperfections never being worse then 'just perceptible'. These results suggest that a further improvement could be obtained by using a tapered quantising law with six bits per sample.

There was a marginal preference for adaptive prediction compared with third-previous-sample prediction. Adaptive prediction provided a noticeable reduction in edge busyness on sharp luminance transitions in areas of a picture containing little or no colour information; this advantage was largely offset, however, by increased quantising errors in coloured areas containing rapid changes in luminance. Also, although the use of adaptive prediction in conjunction with the 5-bit tapered d.p.c.m. quantising law produced very little impairment on the test slides, it was found that this combination of quantising law and adaptive prediction could cause very large quantising errors in areas of very highly saturated colour such as those provided by 100% saturated colour bars (see Section 9.4); this combination is therefore considered unsuitable for broadcasting purposes.

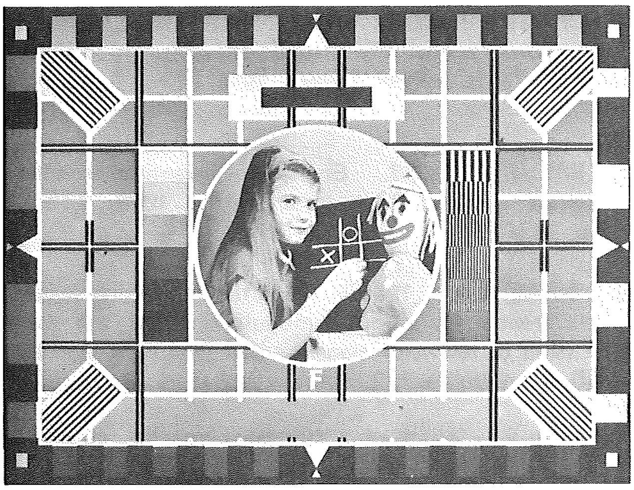
Overall, the tests indicate that for a single coding and decoding operation, broadcast quality pictures can be obtained from a five-bit per sample transmission system using the tapered all d.p.c.m. quantising law and third-previous-sample prediction. For four codecs (combination of coder and decoder) in tandem, it is likely that similar quality pictures could be obtained from a system using six bits per sample. It should be noted that no allowance has been made for the inclusion of extra digits for protection against transmission errors.

TABLE 3

Results of Subjective Tests

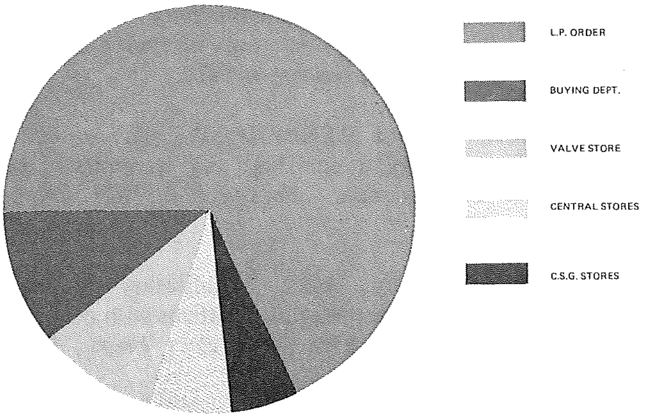
Bits per Sample	System		Slide No.					Mean Grade
	Quantising law	Prediction	1	2	3	4	5	
5	Coarse/fine	$3T_S$ delay	2·7	2·6	3·0	3·4	2·4	2·8 (0·16)
	p.c.m./d.p.c.m.	Adaptive	2·3	2·7	2·8	2·8	2·0	2·5 (0·14)
6	Coarse/fine	$3T_S$ delay	1·2	1·2	1·2	1·4	1·0	1·2 (0·05)
	p.c.m./d.p.c.m.	Adaptive	1·0	1·0	1·2	1·4	1·0	1·1 (0·07)
5	Tapered	$3T_S$ delay	2·2	1·8	1·8	2·0	1·6	1·9 (0·10)
	p.c.m./d.p.c.m.	Adaptive	2·2	1·4	2·0	2·2	1·8	1·9 (0·13)
5	Tapered	$3T_S$ delay	1·4	1·0	1·4	1·8	1·6	1·4 (0·12)
	d.p.c.m. only	Adaptive	1·1	1·0	1·2	1·5	1·5	1·3 (0·10)*

* Grade 6 on 100% saturated colour bars (see Section 9.4)

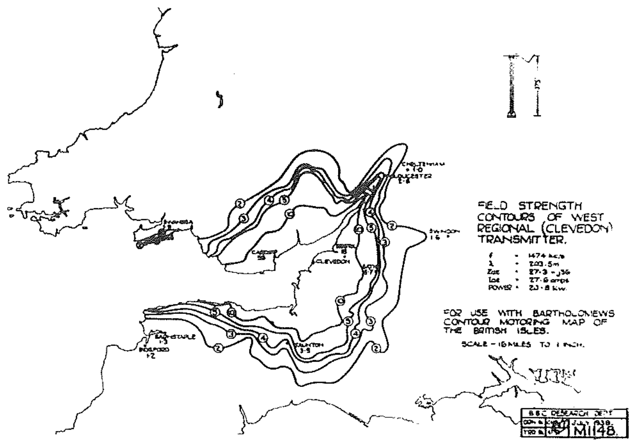


(*a*) Slide 1

(*b*) Slide 2



(*c*) Slide 3



(*d*) Slide 4

(*e*) Slide 5

Fig. 8 - Slides used in subjective tests

7. Conclusions

This report has described various d.p.c.m. and hybrid d.p.c.m./p.c.m. systems for the digital encoding of System I (PAL, 625-line) video signals. All the encoding systems which were examined required the transmission of five or six bits per sample at a sampling rate of about 13·3 MHz i.e. three times the PAL colour subcarrier frequency. Two prediction systems for generating the d.p.c.m. codes were examined; the first used the transmitted value of the third previous sample as the prediction for the current sample value; the second was an adaptive system using either the third previous, or the previous sample value as the prediction signal.

The results obtained from rather limited subjective tests indicate that broadcast quality pictures can be obtained from a five bit d.p.c.m. system using a tapered quantising law (Law 3 in Fig. 6) and third-previous-sample prediction. For similar quality after four coding and decoding operations, it is likely that six bits per sample would be required. The best five-bit hybrid p.c.m./d.p.c.m. system gave slightly inferior results (Grade 1·9 on the 6-point EBU impairment scale as opposed to Grade 1·4 for the d.p.c.m. system) but hybrid systems have the advantage of providing improved ruggedness to transmission errors. Further tests are therefore required concerning the effect of transmission errors, both with and without the employment of error-protection techniques, before a decision can be made as to whether d.p.c.m. or p.c.m./d.p.c.m. provides the better overall coding system. Work carried out elsewhere[9] indicates that up to one additional bit per sample would be required for suitable error protection codes.

8. References

1. Pulse code modulation of video signals: subjective study of coding parameters. BBC Research Department Report No. 1971/40.

2. Digital video: reduction of sampling frequency to 11·9 MHz. BBC Research Department Report No. 1972/36.

3. KRETZMER, E.R. 1952. Statistics of television signals. *Bell Syst. tech. J.*, 2, **31**, 4, pp. 751 – 763.

4. SCHREIBER, W.F. 1956. The measurement of third order probability distributions of television signals. *I.R.E. Trans. Inform. Theory*, 1956, **IT—2**, 3, pp. 94 – 105.

5. LIMB, J.O. 1967. Entropy of quantised television signals. *Proc. Instn elect. Engrs.*, 1968, **115**, 1, pp. 16 – 20.

6. O'NEAL, J.B. 1965. Predictive quantising systems (differential pulse code modulation) for the transmission of television signals. *Bell Syst. tech. J.*, 1966, **46**, 5, pp. 689 – 722.

7. BBC Patent Application No. 3618/71. Reduction of errors in television signals.

8. BBC Patent Application No. 44737/71. Improvements relating to differential pulse code modulation.

9. GOLDING, L.S. 1972. DITEC, a digital television communications system for satellite links. Proceedings of Second International Conference of Digital Satellite Communication, Paris, November 1972.

10. STENGER, L. *and* WENGENROTH, G. 1971. Possibilities of digital encoding and transmission of colour television signals. *Nachrtech Z*, 1971, **24**, 6, pp. 321 – 325.

11. EDWARDSON, S.M. 1966. Translating and transcoding between colour-television systems with common scanning standards. *Proc. Instn elect. Engrs.*, 1967, **114**, 1, pp. 23 – 29.

12. CONNOR, D.J., PEASE, R.F.W. *and* SCHOLE, W.G. 1970. Television coding using two-dimensional spatial prediction. *Bell Syst. tech. J.*, 1971, **50**, 3, pp. 1049 – 1061.

13. BBC Patent Application No. 28953/70. Coarse-fine updating system for digital television.

14. Pulse code modulation of video signals: 8-bit coder and decoder. BBC Research Department Report No. 1970/25.

9. Appendix

9.1. Use of modulo 256 arithmetic

Since the two inputs of both the adder and subtractor shown in Fig. 5 are 8-bit numbers, the resulting output signals should require 9 bits. However, these output signals are reduced to 8 bits by omitting the most significant digit i.e. the digit having a decimal value of 256. The effect of this omission is that 256 is added or subtracted, when necessary, from the outputs of the subtractor and adder so that the resulting signal values always lie in the range 0 to 255. For example if the output of the subtractor in 9-bit form is −32, it is converted into an 8-bit signal of value 256 − 32 i.e. 224; if 60 were then added, the 8-bit output of the adder would be 224 + 60 − 256 = 28. It may be noted that this result is the same as adding 60 to − 32.

This technique of adding or subtracting 256 (or integral multiples of 256) so that all numbers lie in the range 0 to 255 is known as modulo 256 arithmetic.

By using modulo 256 arithmetic in the d.p.c.m. codec it might be thought that the output of the adder $A + E_1$ could be in error by ±256. This difficulty is automatically resolved however because A must lie within the range 0 to 255 and therefore $A + E_1$ must also lie within this range unless the addition of E_1 puts it outside. Since the maximum possible values of E_1 in the equipment described in this report were +8 and −7, the problem arising from the addition of E_1 was eliminated by limiting the values of A to the range from 7 to 247. This latter process was performed in the range limiter shown in Fig. 5.

A second difficulty arising from the use of modulo 256 arithmetic is that the non-linear quantiser receives the same input signal $A - B$ for a small negative difference, which should be accurately quantised and a large positive difference which should be coarsely quantised. This difficulty is overcome in the coder by using the most significant digit omitted from $A - B$ as a control signal which indicates to the non-linear quantiser whether the difference is positive or negative.

9.2. Generation of transmission codes for coarse/fine quantising laws

A suitable form of 5-bit transmission code for use when the d.p.c.m. non-linear quantiser is operating according to Law 1 (see Fig. 6) is shown in Table 4. B_1 to B_8 represent the 8 bits of the difference signal $A - B$ where B_1 is the most significant bit, assuming the ninth bit has already been omitted as explained above. D_1 to D_5 represent the bits in the transmission code.

It will be seen that the first bit D_1 of the transmission code indicates whether the difference is 'large' or 'small'. For small differences, the remaining digits D_2 to D_5 indicate the sign of the difference and the state of the three least significant digits of $A - B$. For these small differences values, B_1 to B_5 are all 0 or all 1 depending on whether the difference is positive or negative; all 8 bits of $A - B$ can

TABLE 4

Transmission Code for Law 1

Size of Difference $A-B$	Transmitted Code D_1	D_2	D_3	D_4	D_5
$+7 \geqslant (A-B) \geqslant -8$ (Small)	0	±	B_6	B_7	B_8
>7 or <-8 (Large)	1	B_1	B_2	B_3	B_4

thus be recovered in the decoder and therefore the error $E_1 = 0$.

For large differences, D_2 to D_5 indicate the state of the four most significant digits of $A - B$. In this case the four least significant digits of the $A - B + E_1$ signal obtained in both the coder and decoder are set to 1, 0, 0, 0. The resulting 8 bits of $A - B + E_1$ are thus B_1 B_2 B_3 B_4 1 0 0 0 and the value of E_1 lies between +7 and −8 inclusive.

As an exception to the rules given above, the four least significant digits of $A - B + E_1$ are set to 1 1 0 0 for values of $A - B$ lying between 8 and 15 or between −9 and −16. As a result, the corresponding output values of $A - B + E_1$ are +12 and −12 respectively instead of +8 and −8, and the corresponding values of E_1 are confined to the range +3 to −4 instead of 0 to 7.

It can be seen that no sign digit is transmitted for large values of the difference signal. As a result, the same large difference code is used for two separate values of the difference signal, one having a positive value 'd' say and the other a negative value (− 256 + d). It is thus possible to transmit 32 separate large difference values by means of only 4 bits. These 32 levels are reduced automatically to 16 levels by specifying the value of the input sample A. For example, if A = 247 then only the 16 negative values could be transmitted while if A = 7, only the 16 positive values could be used.

The transmission code for the 6-bit coarse/fine law can be obtained by adding an extra digit to the 5-bit code shown in Table 4. This sixth digit would represent B_5 for both small and large differences. The values of $A - B$ lying between +15 and −16 inclusive would then be transmitted with 8-bit accuracy while larger differences would be transmitted with 5-bit accuracy.

9.3. 5-bit tapered quantising law

Table 5 gives the characteristics of the 5-bit tapered d.p.c.m. quantising law in more detail than Fig. 6. The slight assymetry between the positive and negative halves of the law was introduced to simplify the instrumentation.

To obtain the coded output signal $A - B + E_1$, the non-linear quantiser first establishes the range of values within which the input $A - B$ has occurred. The limits of each range are indicated by the horizontal lines across

TABLE 5

5-bit tapered d.p.c.m. quantising law

INPUT $(A - B)$		OUTPUT $(A - B + E_1)$		Error E_1
Decimal value	Binary value B_1 B_8	Decimal value	Binary value; changes from input value	Decimal value
(128 to 255) (96 to 127)	(1 X X X X X X X) (0 1 1 X X X X X)	 104	B_1 to B_8 set to 0 1 1 0 1 0 0 0	+8 to −151
80 to 95 64 to 79	0 1 0 1 X X X X 0 1 0 0 X X X X	88 72	B_5 to B_8 set to 1 0 0 0	+8 to −7
56 to 63 48 to 55 40 to 47 32 to 39 24 to 31 16 to 23	0 0 1 1 1 X X X 0 0 1 1 0 X X X 0 0 1 0 1 X X X 0 0 1 0 0 X X X 0 0 0 1 1 X X X 0 0 0 1 0 X X X	60 52 44 36 28 20	B_6 to B_8 set to 1 0 0	+4 to −3
12 to 15 8 to 11	0 0 0 0 1 1 X X 0 0 0 0 1 0 X X	14 10	B_7 and B_8 set to 1 0	+2 to −1
6 or 7 4 or 5 2 or 3	0 0 0 0 0 1 1 X 0 0 0 0 0 1 0 X 0 0 0 0 0 0 1 X	6 4 2	B_8 set to 0	0 or −1
1 0 −1 −2	0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1	1 0 −1 −2	Output same as input	0
− (3 or 4) − (5 or 6) − (7 or 8)	1 1 1 1 1 1 0 X 1 1 1 1 1 0 1 X 1 1 1 1 1 0 0 X	−4 −6 −8	B_8 set to 0	−1 or 0
− (9 to 12) − (13 to 16)	1 1 1 1 0 1 X X 1 1 1 1 0 0 X X	−10 −14	B_7 and B_8 set to	
− (17 to 24) − (25 to 32) − (33 to 40) − (41 to 48) − (49 to 56) − (57 to 64)	1 1 1 0 1 X X X 1 1 1 0 0 X X X 1 1 0 1 1 X X X 1 1 0 1 0 X X X 1 1 0 0 1 X X X 1 1 0 0 0 X X X	−20 −28 −36 −44 −52 −60	B_6 to B_8 set to 1 0 0	−3 to +4
− (65 to 80) − (81 to 96)	1 0 1 1 X X X X 1 0 1 0 X X X X	−72 −88	B_5 to B_8 set to 1 0 0 0	−7 to +8
(− (97 to 128) (− (129 to 256)	(1 0 0 X X X X X) (0 X X X X X X X)	−104	B_1 to B_8 set to 1 0 0 1 1 0 0 0	−7 to +152

Digits marked X may be either 0 or 1

Table 5. The bits marked X in the appropriate range under the column headed 'Input $(A - B)$, Binary value' are then set to the states shown in the column headed 'Output $(A - B + E_1)$, Binary value; changes from input value'. The remaining bits in the output signal $A - B + E_1$ are the same as those in the input signal $A - B$.

9.4. Effect of 5-bit tapered d.p.c.m. quantisation and adaptive prediction on highly-saturated coloured pictures

As mentioned in Section 6.4, it was found that a coding system using adaptive prediction in conjunction

with the 5-bit tapered, d.p.c.m., quantising law (Law 3) could cause very large quantising errors in highly-saturated plain coloured areas of a picture. The reason for this effect is that 100% saturated colours can produce a difference between adjacent samples of up to 160 levels which is 56 levels greater than the maximum difference provided by the tapered quantising law. Therefore, once a transition occurs which takes the predictor into the previous-sample mode, quantising errors of up to 56 levels can occur for the following three samples. After automatic switching back to the third-previous-sample mode, the use of a poorly quantised sample as the predicted sample value can produce a large difference, hence causing the system to switch back to the previous-sample mode. This process could repeat itself over wide areas of saturated colour causing much greater quantising errors than would be obtained by the use of third-previous-sample prediction alone.

SMW/MS

Printed by BBC Research Department, Kingswood Warren, Tadworth, Surrey